The Butterfly Effect.
Bunimovich stadium – simulation by Phillipe Roux,
Smallest possible perturbation?

[Courtesy of John Bollinger]
Source of electrons

Pattern produced from a single slit.

Pattern produced from a double slit.
Fill universe with hard drives $\approx 10^{97}$ bits
→ Sufficient only for a few hundred spins
The Quantum Butterfly Effect
Quantum butterfly effect thought experiment
Missed a screw in step 2!
Fix: deconstruct back to step 2, add screw, rebuild
Spacetime diagram of qubits interacting with neighbors
Snapshots of qubits with all-to-all interactions
Affected region doubles every time step ...
\[\partial_t \tilde{h} = \sum_r \left[ -\gamma_r^+(w) \tilde{h}(w) + \gamma_r^+(w + 1) \tilde{h}(w + e_r) \right] + \]
\[\left[ -\gamma_r^-(w) \tilde{h}(w) + \gamma_r^-(w - 1) \tilde{h}(w - e_r) \right] + \sum_{\langle rr' \rangle} \left[ -\gamma_{b}^+(w_r, w_{r'}) \tilde{h}(w) + \gamma_{b}^+(w_r + 1, w_{r'}) \tilde{h}(w + e_r) \right] + \left[ -\gamma_{b}^-(w_r, w_{r'}) \tilde{h}(w) + \gamma_{b}^-(w_r - 1, w_{r'}) \tilde{h}(w - e_r) \right] + [r \leftrightarrow r']\]

\[\gamma_r^+(w) = \frac{1}{N-1} w(w - 1), \quad \gamma_r^-(w) = \frac{1}{N-1} 3(N - w)w\]

\[\gamma_{b}^+(w_1, w_2) = \frac{g^2}{2N} w_1 w_2, \quad \gamma_{b}^-(w_1, w_2) = \frac{g^2}{2N} 3(N - w_1)w_2.\]
Two related questions:
(1) How do we measure this effect?
(2) How does it manifest in physical properties?
Measuring Quantum Chaos
Reverse!
Fig. 6. Multiple exposures of single proton echoes. The first rf pulse occurs at the beginning of the trace and the second pulse is spaced from the origin at equal intervals for each exposure with the sample at thermal equilibrium. The echo envelope provides a measure of the phase coherence parameter $T_2$.
Reverse!
Needed: inverse DeLorean
NIST Penning trap

Courtesy of John Bollinger, NIST Boulder

4.5 Tesla superconducting solenoid
Speed Limits
Black Holes
[LIGO and VIRGO collaborations, 2016]
Infalling energy doubles per unit time

Anti-de-Sitter spacetime

Anti-de-Sitter spacetime + black hole

[Maldacena]
Affected region doubles every time step ...

[Shenker-Stanford, Kitaev, Sachdev-Ye, ...]
Outlook

• Today we discussed the quantum butterfly effect and its various manifestations in different physical systems

• This is just the tip of the iceberg: quantum chaos has a long history, and there are many new ideas and experiments to explore

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